

The experimental review of $B \rightarrow D^{(*)}\tau\nu_\tau$ decays.

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Experimental studies of $B \rightarrow D^{(*)}\tau\nu_\tau$ decays, are reported. The results are based on large data samples collected at the $\Upsilon(4S)$ resonance with the Belle detector at KEKB and the BABAR detector at the SLAC PEP-II asymmetric energy e^+e^- colliders.

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1 Introduction

B decays to τ leptons represent a broad class of processes that can provide interesting tests of the Standard Model (SM) and its extensions. Of particular interest are the modes presented in this report, the semi-leptonic decays $B \rightarrow \overline{D}^{(*)} \tau^+ \nu_\tau$ [1, 2, 3, 4]¹.

In the SM semileptonic B decays to τ leptons occur at tree level. Branching fractions are predicted to be smaller than those to light leptons. The predicted branching fractions, based on the SM, are around 1.4% and 0.7% for $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ and $B^0 \rightarrow D^- \tau^+ \nu_\tau$, respectively (see *e.g.*, [5]).

B meson decays with $b \rightarrow c \tau \nu_\tau$ transitions, due to the large mass of the τ lepton, are sensitive probes of models with extended Higgs sectors[6][7]. The semileptonic B decays to tau provide new observables sensitive to New Physics such as polarizations, which cannot be accessed in leptonic B decays. In multi-Higgs doublet models, substantial departures from the SM decay rate could occur for $B \rightarrow \overline{D} \tau^+ \nu_\tau$. Smaller departures are expected for $B \rightarrow \overline{D}^* \tau^+ \nu_\tau$, however they provide cleaner sample and D^* polarisation that can be used to enhance a sensitivity to NP effects.

Difficulties related to multiple neutrinos in the final states cause that there is little experimental information about decays of this type. Prior to the B-factories era, there was only inclusive measurement of $\mathcal{B}(B \rightarrow c \tau^+ \nu_\tau) = (2.48 \pm 0.26)\%$ from LEP[8].

2 Analysis techniques

At B -factories B decays to multi-neutrino final states can be observed via the recoil of accompanying B meson (B_{tag}). The B_{tag} can be reconstructed inclusively from all the particles that remain after selecting B_{sig} candidates or exclusively in several hadronic decay modes. The remaining charged particles and photons are required to be consistent with the hypothesis that they are coming from $B \rightarrow D^{(*)} \tau \nu_\tau$ decays. Choice of the τ , D or D^* decay modes, as well as the methods of the B_{tag} reconstruction, depend on particular analysis requirements on purity and signal extraction procedure, etc.

2.1 Exclusive reconstruction of B_{tag} in hadronic modes

In BaBar results the B_{tag} candidates are reconstructed in 1114 final states $B_{\text{tag}} \rightarrow D^{(*)} Y^\pm$. These final states arise from the large number of ways to reconstruct the D and D^* mesons within the B_{tag} candidate and the possible pion and kaon combinations within the Y system. The Y^\pm system may consist of up to six light hadrons (π^\pm, π^0, K^\pm , or K_S).

¹Charge conjugate modes are implied throughout this report unless otherwise stated.

For Belle case, the B_{tag} candidates are reconstructed in the following decay modes: $B_{\text{tag}}^+ \rightarrow \overline{D}^{(*)0} h^+$, and $B_{\text{tag}}^0 \rightarrow \overline{D}^{(*)-} h^+$, where h^+ can be π^+ , ρ^+ , a_1^+ or $D_s^{(*)+}$.

The selection of B_{tag} candidates is based on the energy substituted mass $m_{\text{ES}} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$ (called m_{bc} in Belle) and the energy difference $\Delta E \equiv E_B - E_{\text{beam}}$. Here, E_B and p_B are the reconstructed energy and momentum of the B_{tag} candidate in the e^+e^- center-of-mass (CM) system, and E_{beam} is the beam energy in the CM frame.

2.2 Inclusive reconstruction of B_{tag} in hadronic modes

The inclusive tagging was, up to now, exploited only by Belle collaboration[1, 2].

With this method the reconstruction starts from B_{sig} candidates. Reconstruction of $D^{(*)}$ on the signal side strongly suppresses the combinatorial and continuum backgrounds. Once a B_{sig} candidate is found, the remaining particles that are not assigned to B_{sig} are used to reconstruct the B_{tag} decay. The consistency of a B_{tag} candidate with a B -meson decay is checked using the beam-energy constrained mass and the energy difference variables: $M_{\text{tag}} = \sqrt{E_{\text{beam}}^2 - \mathbf{p}_{\text{tag}}^2}$, $\mathbf{p}_{\text{tag}} = \sum_i \mathbf{p}_i$, and $\Delta E_{\text{tag}} = E_{\text{tag}} - E_{\text{beam}}$, $E_{\text{tag}} = \sum_i E_i$, \mathbf{p}_i and E_i denote the 3-momentum vector and energy of the i 'th particle. All quantities are evaluated in the $\Upsilon(4S)$ rest frame. The summation is over all particles that are left after reconstruction of B_{sig} candidates.

To suppress background and improve the quality of the B_{tag} selection, additional requirements are imposed like: zero total event charge; no charged leptons in tag side; zero net proton/anti-proton number. The requirement of the high missing mass results in flat M_{tag} distributions for most background components, while the distribution of the signal modes peaks, at the B mass. The main sources of the peaking background are the semileptonic decays $B \rightarrow \overline{D}^* l^+ \nu_l$ and $B \rightarrow \overline{D}^{(*)} \pi l^+ \nu_l$ (including $\overline{D}^{**} l^+ \nu_l$).

3 $B \rightarrow D^{(*)} \tau^+ \nu_\tau$ with inclusive hadronic tag

Belle collaboration reported the first observation of an exclusive decay with the $b \rightarrow c \tau \nu_\tau$ transition[1], in the $B^0 \rightarrow D^{*+} \tau^- \nu_\tau$ channel using inclusive B_{tag} reconstruction in a data sample containing $535 \times 10^6 B\overline{B}$ pairs. The $\tau^- \rightarrow e^- \nu_e \nu_\tau$ and $\tau^- \rightarrow \pi^- \nu_\tau$ modes are used to reconstruct τ lepton candidates.

The observed signal of 60_{-11}^{+12} events for the decay $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ was extracted from M_{tag} distribution.

A new analysis for $B^+ \rightarrow D^{(*)0} \tau^+ \nu_\tau$ was performed in a sample of $657 \times 10^6 B\overline{B}$ pairs[2]. The signal and combinatorial background yields are extracted from an extended unbinned maximum likelihood fit to the M_{tag} and P_{D^0} (momentum of D^0 from B_{sig} measured in the $\Upsilon(4S)$ frame) variables. The $\tau^+ \rightarrow e^+ \nu_e \nu_\tau$, $\tau^+ \rightarrow \pi^+ \nu_\tau$, and in addition $\tau^+ \rightarrow \mu^+ \nu_\tau$ modes are used to reconstruct τ lepton candidates. In

total, 13 different decay chains are considered, eight with \overline{D}^{*0} and five with \overline{D}^0 in the final states. The fits are performed simultaneously to all data subsets. In each of the sub-channels, the data was described as the sum of four components: signal, cross-feed between $\overline{D}^{*0}\tau^+\nu_\tau$ and $\overline{D}^0\tau^+\nu_\tau$, combinatorial and peaking backgrounds. The common signal branching fractions $\mathcal{B}(B^+ \rightarrow \overline{D}^{*0}\tau^+\nu_\tau)$ and $\mathcal{B}(B^+ \rightarrow \overline{D}^0\tau^+\nu_\tau)$, and the numbers of combinatorial background in each sub-channel are free parameters of the fit, while the normalisations of peaking background contributions are fixed to the values obtained from the rescaled MC samples. The signal yields and branching fractions for $B^+ \rightarrow \overline{D}^{(*)0}\tau^+\nu_\tau$ decays are related assuming equal fractions of charged and neutral B meson pairs produced in $\Upsilon(4S)$ decays. All the intermediate branching fractions are taken from the PDG compilation [8].

The signal yields are $446_{-56}^{+58} B^+ \rightarrow \overline{D}^{*0}\tau^+\nu_\tau$ events and $146_{-41}^{+42} B^+ \rightarrow \overline{D}^0\tau^+\nu_\tau$ events.

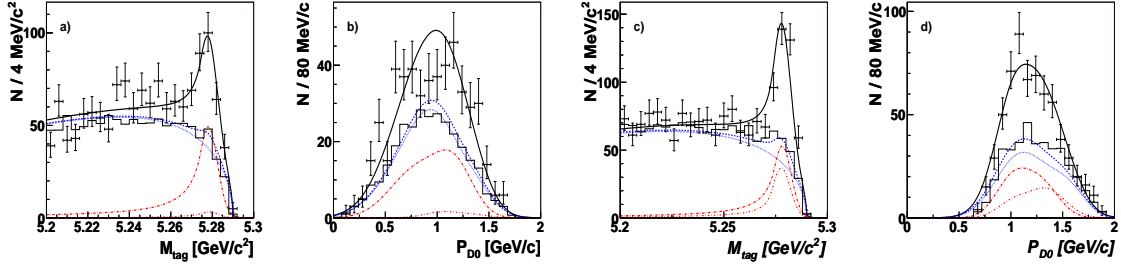


Figure 1: The fit projections to M_{tag} , and P_{D^0} for $M_{\text{tag}} > 5.26 \text{ GeV}/c^2$ (a,b) for $\overline{D}^{*0}\tau^+\nu_\tau$, (c,d) for $\overline{D}^0\tau^+\nu_\tau$.

4 $B \rightarrow D^{(*)}\tau^+\nu_\tau$ with exclusive hadronic tags

Babar collaboration presented measurements of the semileptonic decays $B^- \rightarrow D^0\tau^-\overline{\nu}_\tau$, $B^- \rightarrow D^{*0}\tau^-\overline{\nu}_\tau$, $B^0 \rightarrow D^+\tau^-\overline{\nu}_\tau$, $B^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$, and $B^0 \rightarrow D^+\tau^-\overline{\nu}_\tau$ [3]. The data sample consists of $232 \times 10^6 \Upsilon(4S) \rightarrow B\overline{B}$ decays. The events are selected with a D or D^* meson and a light lepton ($= e$ or μ) recoiling against a fully reconstructed B meson.

The fit is performed to the joint distribution of lepton momentum and missing mass squared, m_{miss}^2 , to distinguish signal $B \rightarrow D^{(*)}\tau^-\nu_\tau$ ($\tau^- \rightarrow l^-\overline{\nu}_l\nu_\tau$) events from the backgrounds, predominantly $B \rightarrow D^{(*)}l^-\overline{\nu}_l$. The fit is performed simultaneously in four signal channels. Figure 2 shows projections in m_{miss}^2 for the four signal channels, showing both the low m_{miss}^2 region, which is dominated by the normalisation modes $B \rightarrow D^{(*)}l\nu_l$, and the high m_{miss}^2 region, which is dominated by the signal mode $B \rightarrow D^{(*)}\tau\nu_\tau$.

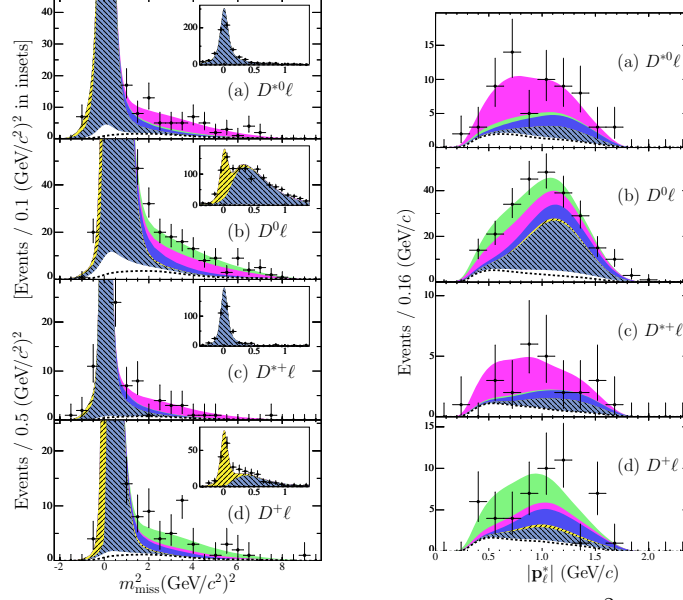


Figure 2: Distributions of events and fit projections in m_{miss}^2 (left) and in $|P_l^*|$ for the four final states: $D^{*0}l^-$, D^0l^- , $D^{*+}l^-$, and D^+l^- . The normalisation region $m_{\text{miss}}^2 \approx 0$ is shown with finer binning in the insets. The $|P_l^*|$ is shown in the signal region, $m_{\text{miss}}^2 > 1(\text{GeV}/c^2)^2$. The fit components are combinatorial background (white, below dashed line), charge-crossfeed background (white, above dashed line), the $B \rightarrow Dl\nu_l$ normalisation mode (/ / hatching, yellow), the $B \rightarrow D^*l\nu_l$ normalisation mode (\ \ hatching, light blue), $B \rightarrow D^{**}l\nu_l$ background (dark, or blue), the $B \rightarrow D\tau\nu_\tau$ signal (light grey, green), and the $B \rightarrow D^*\tau\nu_\tau$ signal (medium grey, magenta).

Babar measures the branching-fraction ratios $R(D) = B(B \rightarrow D\tau\nu_\tau)/B(B \rightarrow Dl\nu_l)$ and $R(D^*) = B(B \rightarrow D^*\tau\nu_\tau)/B(B \rightarrow D^*l\nu_l)$ and, from a combined fit to B^+ and B^0 channels, approximately 67 $B \rightarrow D\tau\nu_\tau$ and 101 $B \rightarrow D^*\tau\nu_\tau$ signal events are observed, corresponding to resulting ratios $R(D) = (41.6 \pm 11.7 \pm 5.2)\%$ and $R(D^*) = (29.7 \pm 5.6 \pm 1.8)\%$, where the uncertainties are statistical and systematic. The signal significances are 3.6σ and 6.2σ for $R(D)$ and $R(D^*)$, respectively. Normalising to world averaged $B^- \rightarrow D^{(*)0}l^-\nu_l$ branching fractions[8], they obtain $B(B \rightarrow D^*\tau\nu_\tau) = (0.86 \pm 0.24 \pm 0.11 \pm 0.06)\%$ and $B(B \rightarrow D^*\tau\nu_\tau) = (1.62 \pm 0.31 \pm 0.10 \pm 0.05)\%$, where the additional third uncertainty is from the normalisation mode. They present for the first time, distributions of the lepton momentum, $|p_l^*|$, and the squared momentum transfer, q^2 .

Belle collaboration presented similar study based on 604.5 fb^{-1} of the data sample[4]. The $B \rightarrow D\tau\nu_\tau$ and $B \rightarrow D^*\tau\nu_\tau$ signals are extracted using unbinned extended maximum likelihood fits to the two-dimensional $(m_{\text{miss}}^2, E_{\text{extra}}^{\text{ECL}})$ distributions obtained after the selection of the signal decays. The B^+ and B^0 samples are fitted separately. The

cross talk between the two tags is found to be small. Then for each B^0 and B^+ tag, a fit is performed simultaneously to the two distributions for the $D\tau\nu_\tau$ and $D^*\tau\nu_\tau$. The fit components are two signal modes; $B \rightarrow D\tau\nu_\tau$ and $B \rightarrow D^*\tau\nu_\tau$, and the backgrounds from $B \rightarrow D\ell\nu_e$, $B \rightarrow D^*\ell\nu_e$ and other processes. For the fitting of the $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$ distribution, the $D\tau\nu_\tau$ cross feed and $D\ell\nu_\ell$ background are not included, because their contribution are found to be small.

The results for the four ratios are listed in Table2, Taking into account the branching fractions for the $B \rightarrow D^*\ell\nu_l$ normalisation decays, reported in [8] , the branching fractions for the $B \rightarrow D^*\tau\nu_\tau$ decays are obtained and listed in Table1.

4.1 Summary

Experimentally all modes are clearly established, with significance at least 3σ (over 5σ for D^* modes). They are observed in both experiments and there is still a room for improvement since the results are not based on full statistics.

Table 1: Summary of branching-fractions for $B \rightarrow D^{(*)}\tau\nu_\tau$ decays([%]), where the first error is statistical, the second is systematic, and the third is due to the branching fraction error for the normalisation modes. In brackets are significances, after including the systematics($[\sigma]$).

Mode	Belle[1][2]	BaBar[3]	Belle[4]
\overline{D}^{*0}	$2.12^{+0.28}_{-0.27} \pm 0.29(8.1)$	$2.25 \pm 0.48 \pm 0.22 \pm 0.17(5.3)$	$3.04^{+0.69}_{-0.66}^{+0.40}_{-0.47} \pm 0.22(3.9)$
D^{*-}	$2.02^{+0.40}_{-0.37} \pm 0.37(5.2)$	$1.11 \pm 0.51 \pm 0.04 \pm 0.04(2.7)$	$2.56^{+0.75}_{-0.66}^{+0.31}_{-0.22} \pm 0.10(4.7)$
\overline{D}^0	$0.77 \pm 0.22 \pm 0.12(3.5)$	$0.67 \pm 0.37 \pm 0.11 \pm 0.07(1.8)$	$1.51^{+0.41}_{-0.39}^{+0.24}_{-0.19} \pm 0.15(3.8)$
D^-	-	$1.04 \pm 0.35 \pm 0.15 \pm 0.10(3.3)$	$1.01^{+0.46}_{-0.41}^{+0.13}_{-0.11} \pm 0.10(2.6)$

Table 2: The measured branching-fraction ratios for individual $D^{(*)}$ states for analysis based on exclusive B_{tag} reconstruction. The first errors are the statistical and the second errors are the systematic.

	BaBar[3]	Belle[4]
$R(\overline{D}^0)$	$(31.4 \pm 17.0 \pm 4.9)\%$	$(70^{+19}_{-18}^{+11}_{-9})\%$
$R(\overline{D}^{*0})$	$(34.6 \pm 7.3 \pm 3.4)\%$	$(47^{+11}_{-10}^{+6}_{-7})\%$
$R(D^-)$	$(48.9 \pm 16.5 \pm 6.9)\%$	$(48^{+22}_{-19}^{+6}_{-5})\%$
$R(D^{*-})$	$(20.7 \pm 9.5 \pm 0.8)\%$	$(48^{+14}_{-12}^{+6}_{-4})\%$

The current experimental status of semi tauonic B decays is summarized in Tables 2 and 1.

There is no yet HFAG experimental average of the semi-tauonic B decays. Taking into account all available experimental results from Belle and Babar a naive weighted averages can be calculated²:

- $\mathcal{B}(B^+ \rightarrow \overline{D}^{*0} \tau^+ \nu_\tau) = (2.36 \pm 0.27)\%$
- $\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = (1.70 \pm 0.34)\%$
- $\mathcal{B}(B^+ \rightarrow \overline{D}^0 \tau^+ \nu_\tau) = (0.89 \pm 0.20)\%$
- $\mathcal{B}(B^0 \rightarrow D^- \tau^+ \nu_\tau) = (1.03 \pm 0.30)\%$

These results are consistent with the SM but, given the uncertainties, there is still a room for a sizeable non-SM contribution. The Super B-factories with ≈ 50 times higher statistics should measure these modes with much higher precision. Of particular interest will be measurements of differential distributions.

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²it takes into account correlations in systematic for Belle results